Agricultural Systems 169 (2019) 49–57

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Agricultural area losses and pollinator mismatch due to climate changes endanger passion fruit production in the Neotropics

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ARTICLE INFO

Keywords:
Carpenter bees
Maxent
Passiflora
Pollination services
Tropical pollination
Xylocopa

ABSTRACT

Pollinator diversity and abundance are declining in the agricultural landscapes of some parts of the world along with the pollination services they provide. Among an array of reasons, climate change has been pointed out as a major player and studies suggest strong negative impacts on agricultural pollination toward the end of the 21st century. In this study, we investigated for the first time the concomitant effect of climate changes on a tropical crop, passion fruit (*Passiflora edulis*), and its two main pollinator bee species (*Xylocopa frontalis* and *X. grisescens*) in the Neotropics considering two of the IPCC environmental scenarios, RCP 4.5; RCP 8.5 (Representative Concentration Pathways), and in the years 2060 and 2080. We have shown that the climate changes may lead to changes in the natural ranges of *Xylocopa* bees, with considerable loss of habitable area (*X. frontalis*, RCP 4.5 = −27.3 to −15.4%; RCP 8.5 = −57.7 to −47.9%; *X. grisescens*, RCP 4.5 = −15.4 to −27.81%; RCP 8.5 = −23.5 to −35.3%), as well as for cropping passion fruit (RCP 4.5 = −44. 9 to −51.3%; RCP 8.5 = −42.9 to −64.8%), for years 2060 and 2080, respectively. We also predicted a potential reduction between 31.9% and 54.9% in the overlapping of the remaining suitable areas for the bees and passion fruit, increasing the potential spatial mismatch between the crop and its pollinators. Based on the models forecast of climate changes, we conclude that the suitable areas to co-occurrence of passion fruit crop and its effective pollinators will be largely affected in the Neotropics and steps to mitigate the effects of the climate changes should be taken to ensure viable population of pollinators in the remaining suitable areas for both bees and the crop.

1. Introduction

The pollination service can be considered one of the most important ecosystem services in the world. Pollinators play a key role in the maintenance and reproduction of wild plants species, in addition to ensuring yield to many agricultural crops (Klein et al., 2007; Potts et al., 2016; Pufal et al., 2017). It is estimated that 35% of agricultural crop production (Klein et al., 2007) and 87.5% of flowering plants in the world (Ollerton et al., 2011) at some point depend on a pollinator (Brown et al., 2016; IPBES, 2016).

However, pollinators have declined considerably in the agricultural landscapes of some parts of the world and, as a consequence, also the pollination service they provide (Biesmeijer et al., 2006; Potts et al., 2010). This fact is known as pollinator decline and could affect significantly the maintenance and reproduction of plants species, ecosystem stability, agricultural crop production, food security and human well-being (Potts et al., 2010).

Evidence points to several causes of pollinator decline, such as habitat loss and fragmentation, plagues, diseases, pathogen spillover, invasive species, and climate changes (Freitas et al., 2009; Potts et al., 2010; Cameron et al. 2011; Meeus et al., 2012; Potts et al., 2016; Brown et al., 2016). Among these, climate changes may have an impact on pollinators in a progressive way, which is already well characterized by the gradual global warming and mean temperature increase, or in the form of extreme events, which are still poorly understood (Brown et al., 2016) even though they already occur in several regions of the globe (IPCC, 2013). Natural fires, hurricanes and tornadoes, torrential rains out of the season, as well as heat waves and droughts, are becoming more frequent and intense in the Neotropics (Freitas et al., 2009). Heat waves and droughts may also be responsible for the strong reduction observed in the population of some species of bumble bees and butterflies in parts of Europe and UK, with potential threats to local

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https://doi.org/10.1016/j.agsy.2018.12.002
Received 25 July 2018; Received in revised form 30 November 2018; Accepted 3 December 2018
Available online 07 December 2018
0308-521X/

extinction of these pollinators (Rasmont and Iserbyt, 2012; Oliver et al., 2015).

Climate change has generated concerns about potential effects on plant and animal biodiversity as well as the pollination services in agriculture (Potts et al., 2016; Brown et al., 2016; Settele et al., 2016). For example, it is known that changes in climate patterns may drive to spatial and temporal mismatch of plants species and their pollinators (Kjøhl et al., 2011; Settele et al., 2016), affecting directly the plant-pollinator interaction with the extinction of local pollinators and reducing network robustness (Rasmont and Iserbyt, 2012; Burkle et al., 2013; Vanbergen et al., 2013; Oliver et al., 2015). Therefore, the spatial and temporal mismatch between pollinators and agriculture crops represents a potential risk to agricultural production (Settele et al., 2016).

There are several consistent studies showing the effects of climate change on agricultural crops (Lobell et al., 2011, Challinor et al., 2014, Rosenzweig et al., 2014) and pollinators (Bartomeus et al. 2013; Burkle et al., 2013; Vanbergen et al., 2013; Giannini et al., 2013; Elias et al., 2017), but only a few studies investigated how the changes in climate patterns may act concomitantly on agricultural crops and their pollinators (Rader et al., 2013; Polce et al., 2014; Imbach et al., 2017).

Such studies are particularly interesting for agricultural species vulnerable to pollinator decline, such as the passion fruit crop (*Passiflora edulis* Sims f. *flavicarpa*). Passion fruit is an important native South American crop that provides yields during most of the year, both for small farmers and farm companies. Brazil is the world's largest passion fruit producer (~60% of the world production), followed by Indonesia (~10%), India (~9%) and Colombia (~5%) (USAID, 2014). Nowadays, the value of passion fruit crop production in Brazil is around US$ 340 million and its production diversifies in fresh fruit and fresh juice (IBGE, 2017; FAOSTAT, 2017). Adequate pollination is already an issue for passion fruit flowers that rely on scarce large-sized bees, and understanding potential future threats to the pollinator-crop relationship is crucial to this agricultural product (Silva et al., 2014; Freitas et al. 2017).

Passion fruit flowers are isolated, large, hermaphroditic, presenting a columnar structure at the center called androgynophore, with raised reproductive organs at different heights (heterostyly). The flower is protandrous, releasing pollen before the stigma is receptive (Freitas and Oliveira-Filho, 2001; Cobert and Willmer, 1980). In addition, the passion fruit is self-incompatible, requiring pollen produced by another plant for pollination to produce seeds and fruit (Bruckner et al., 1993).

All these barriers prevent self-pollination and cause dependence on large bees both to touch the flower's reproductive organs during the visit by acquiring pollen in their bodies and to distribute the pollen to receptive stigmas of more distant flowers belonging to other plants (Freitas and Oliveira-Filho, 2003; Augusto et al., 2012; Yamamoto et al., 2012). In this condition, large bees of genus *Xylocopa* are the effective pollinators of passion fruit crop (Siqueira et al., 2009; Junqueira et al., 2013).

The high dependence of this plant species on a few specialized wild pollinators makes the passion fruit crop a good model for studying the impact of climate change on agricultural pollination services. Therefore, changes in the occurrence of bees of the genus *Xylocopa* in a Brazilian biome where the passion fruit crop is important were investigated by Giannini et al. (2013). In the present work, we used spatial distribution modeling (SDM) to evaluate the potential consequences of climate changes to the suitability of occurrence of both the main pollinator bees species of passion fruit crop, *Xylocopa frontalis* and *X. grisescens*, and the passion fruit crop (*P. edulis*), and an overlapping of bees and crop in the whole Neotropic region considering two of the IPCC environmental scenarios (2013), RCP = 4.5; RCP = 8.5, in the years 2060 and 2080.

2. Material and methods

2.1. Biotic data

We analyzed two species of carpenter bees, *X. frontalis* Oliver, 1789 and *X. grisescens* Lepeletier, 1841. The criteria for choosing these bees is because they are the most effective pollinators of passion fruit flowers and have the greatest abundance and distribution in the Neotropical area cultivated with this crop. Other *Xylocopa* species are either less efficient as pollinators or occur in smaller areas than *X. frontalis* and *X. grisescens* (Freitas and Oliveira-Filho, 2003; Siqueira et al., 2009; Yamamoto et al., 2012). The visitation of these large-sized bees to passion fruit flowers is essential for fruit set both due to the physical and physiological barriers presented by this crop to avoid self-pollination (see above) as well as the great distance between the nectar chamber and the reproductive organs making impossible to smaller insects to make contact with stamens or stigmas while collecting nectar. The absence of large insects, mainly large *Xylocopa* bees such as *X. frontalis* and *X. grisescens* in passion fruit plantations leads to almost no fruit set and total economic loss. Introduction of 25 nests of *X. frontalis* and *X. grisescens* per hectare have increased fruit set between 92% to 700% in Brazil, depending on the number of these bees naturally occurring in the area (Camillo, 1996; Freitas and Oliveira-Filho, 2003). An alternative is hand pollination of the flowers, but this practice increases production costs by 12% in average, reducing profits (Junqueira et al., 2013).

Current territories of the studied *Xylocopa* species were obtained though literature review (articles, systematic surveys, dissertation and thesis), as well as systematic searches in entomological collections available in data portals provided by the *SpecieLink* and *Global Biodiversity Information Facility* – GIBF. These are the most comprehensive data available on the occurrence of carpenter bees, the two main species studied, and covers most of their natural areas in the Neotropics.

The data generated 371 occurrence points to *X. frontalis* and 188 occurrence points to *X. grisescens*. We observed that some occurrence point records had errors (e.g. duplicated data, incomplete information or incorrect coordinates) related to the coordinate positions. Thus, we did a cleaning and extraction of the occurrence errors points that did not represent the actual spatial distribution of these species (Polce et al. 2014). A detailed methodology is presented in the Data in Brief article (see in Bezerra et al., 2018).

To obtain coordinate points of passion fruit crops, we used the county agricultural production database available on the Brazilian Institute of Geography and Statistics (IBGE) website. Thus, 1195 counties where passion fruit crops were cultivated in the last ten years were taken as base to point coordinates (see Supplementary material).

2.2. Climate data

A total of 19 layers of bioclimatic variables for current scenarios were obtained through *Worldclim* (Hijmans et al. 2005), each layer having spatial resolution of 2.5 arc minutes (Cells with size ~ 4.5 km resolution at the equator). We also used 19 layers of bioclimatic variables with the same resolution for future scenarios. Forecasts for the future clime conditions were obtained based on the climatic changes for the years 2060 and 2080, considering the scenarios RCP 4.5 and RCP 8.5 (Representative Concentration Pathways; IPCC (AR5), developed by Hadley Center Global Environmental Model (HadGEM2-ES)). Thus, based on the recently published 5th Assessment Report IPCC (AR5), the scenarios RCP 4.5 and 8.5 Wm^{-2} radioactive forcing level, correspond to the moderate and pessimistic scenarios, respectively. In other words, the forecast of global mean temperature increase in the scenario moderate is 1.4 to 1.8 °C and in the pessimistic scenario is 2.0 to 3.7 °C (IPCC - AR5, 2013).

The correlation levels between bioclimatic variables were obtained

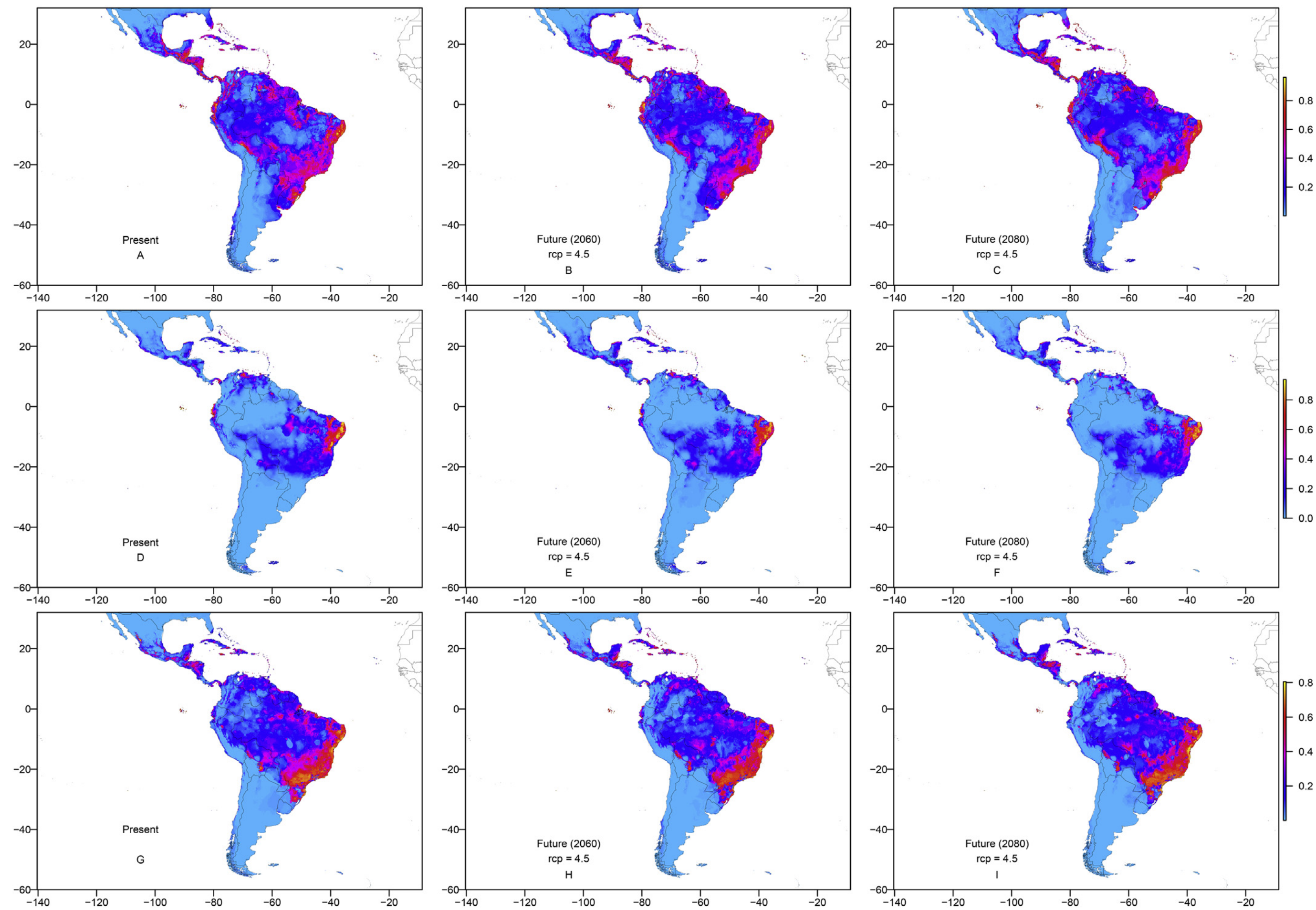

Fig. 1. Maps of the forecast models for *Xylocopa frontalis* (A, B, C), *Xylocopa grisescens* (D, E, F) and *Passiflora edulis* (G, H, I) in the projection by the RCP 4.5 in years 2060 and 2080.

using Pearson's correlation coefficient and Principal Components Analysis (PCA) for each pairwise comparison of the 19 climatic variables. When two or more variables presented strong correlation ($r \geq |0.75|$), then only the most explanatory variable was selected according to PCA. These variables were removed to prevent multicollinearity of the models, i.e., the coefficient estimates become unstable and difficult to interpret, compromising the models. The lowest contribution variables were excluded from the final model of all species. The number of bioclimatic variables left in the models was 8 to 10 for *X. frontalis;* 6 to 8 for *X. grisescens* and 6 to 9 for the passion fruit crop (see Supplementary material).

2.3. Models building

The Species Distribution Modeling (SDM) was developed using the package Dismo v.1.1-4 (Hijmans et al., 2016), R language (R Development Core Team, 2016). For this, we used the ecological niche modeling, applying the MaxEnt (Maximum entropy) algorithm (Phillips et al., 2006). The calibration and validation of the models was performed with 10 replications with MaxEnt combinations (QPTH (quadratic + product + threshold + hinge) and QPH (quadratic + product + hinge), with level of regulation equal to 1.0 in total of three calibrations for each model and maximum of 500 interactions for each model. A total of 20% of the occurrence points was used as *test* and randomly chosen for each species. However, we also applied the lowest scores of omission rate (*10 percentile omission rate*, or $OR_{10\%}$) when calculating the predictability of recovery of these 20% in the model constructed was compared with the highest scores of Area Under the Curve (AUC) to denote suitability (Soley-Guardia et al. 2014). The high AUC scores indicated that the model is based on information, if compared to a random model without information, which the AUC score was 0.50. The AUC scores (close to 1.0) indicated a good performance of the models (see Table 1 in Bezerra et al. 2018).

2.4. Current and future co-occurrence

To map overlapping ranges, a random set of pseudo-absence data to each species was required to the whole study area (Latitude, 32° East to −60° West; Longitude, 24° North to −125° South). The random set of pseudo-absence data were grouped into five groups (1 test group and 4 training groups) per species with a total of 200 pseudo-occurrence points for each group. Therefore, we determined the cutoff with Dismo v1.1–4 package (Hijmans et al., 2016), and with Biomod2 v.3.3–7 package (Thuiller et al., 2014) in R language (R Development Core Team), and we perform a binary transformation of the models, so they could be compared a posteriori.

Thus, after binary transformations for each model, each of the maps was compared between the current scenario and future scenario. We also compared the passion fruit map scenarios with the respective bee species map scenarios separately and for the two bees acting together. In this way, it was possible to estimate the area (Km^2) suitable for each species in the current scenario and the change in the spatial distribution range of the species in the future scenarios, as well as the overlap in area (Km^2) that are suitable for the crop, for the bees species and for all species acting together.

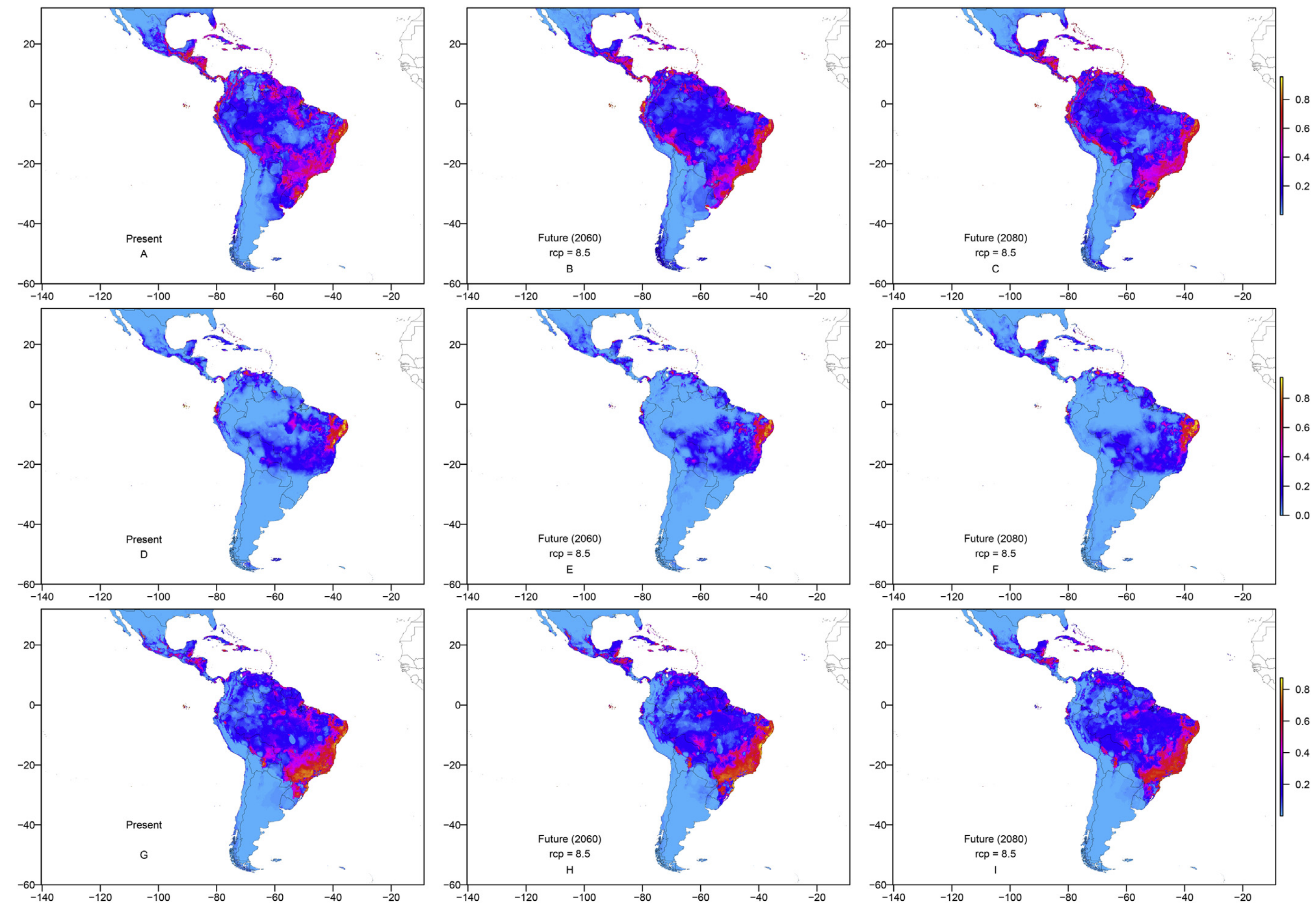

Fig. 2. Maps of the forecast models for *Xylocopa frontalis* (A, B, C), *Xylocopa grisescens* (D, E, F) and *Passiflora edulis* (G, H, I) in the projection by the RCP 8.5 in years 2060 and 2080.

3. Results

3.1. Occurrence of Xylocopa species and the passion fruit crop

Currently, the number of occurrence points recorded in the Neotropics for the studied species of carpenter bees was 271; 199 for *X. frontalis* and 72 for *X. grisescens*, while 1195 Brazilian counties were recorded for passion fruit cultivation from 2006 to 2015. According to the occurrence points sampled, *X. frontalis* has a larger spatial distribution in relation to *X. grisescens*, whose the occurrence points were restricted to Brazil. As for the passion fruit crop, the occurrence points showed a high concentration of cultivated areas in the Northeast, Southeast and Southern of Brazil (see Fig. 1-3 in Bezerra et al., 2018). These data represent the best information available at the present data to both the bee species and passion fruit. Despite the existence of some gaps in the points of occurrence in remoted forested areas, probably due to lack of sampling, the continuation of their presence in most of the covered areas gives high level of certainty.

3.2. Modeling of current scenarios and future scenarios

The forecast model for the current spatial distribution of *X. frontalis* suggests that the central region of Brazil presents unsuitable areas to its occurrence with the lowest potential suitability for area of occurrence, followed by Chile and Colombia, Venezuela, Peru and Bolivia and Paraguay (less than 20%) and regions where the presence of this species is not expected (e.g. Patagonia). On the other hand, suitable areas with high potential for the species occurrence (above 60%) are concentrated in Brazil, although some adequate, but fragmented, areas can also be observed in other countries (Fig. 1A).

The prediction for *X. grisescens* current spatial distribution showed that potential adequate areas for occurrence (over 60%) are concentrated predominantly in the Atlantic Forest, the Brazilian Semi-arid and some areas in the Ecuador coast, although no records of this species are known for the latter country. Other regions (e.g. Amazonia and Southern of Brazil) have a lower occurrence potential (less than 10%), as well as few other areas in the Neotropics, with prevalence of unsuitable areas for this bee species (Fig. 1D). The maps obtained through forecast models present a spatial distribution compatible with the present known range distribution of both bee species, except for *X. grisescens* in the few Ecuador coastal areas.

Regarding the spatial distribution of the passion fruit crop, forecast models suggest an extensive range area suitable for cropping in Brazil. There are also some regions in Bolivia and Central America countries (suitability potential above 60%) whose ecological and climates conditions are adequate for cropping passion fruit. However, we observed in the maps that a part of the Neotropical region presents areas with less potential adequacy and unsuitable for this crop (less than 20%), among them the Amazonia and most South America countries (Fig. 1G). The map obtained through the spatial distribution modeling of the crop currently covered all the area presented by IBGE (IBGE, 2017).

The forecast models obtained for both bee species and passion fruit crop received AUC scores equals to or superior than 0.90, except the RCP 4.5 (2060) passion fruit crop model for which the score was 0.8981. Models with AUC scores above 0.90 were considered accurate and models with AUC score 0.89 were considered good predictors (see

Table 1 in Bezerra et al., 2018).

According to the results, the potential occurrence areas for both bee species and passion fruit crop under moderate scenarios (RCP 4.5; 2060 and 2080) will undergo considerable changes in the spatial distribution of these species in the Neotropics (Fig. 1). In general, the potential occurrence areas for *X. frontalis, X. grisescens* and *P. edulis* which in the current scenario is less than 40%, will face an even greater reduction in the future scenarios. However, despite reducing in size, they will increase the present adequacy probability from 60% to around 80%. In other words, areas suitable for cropping passion fruit and the presence of its pollinators will reduce in size but will become more suitable to presence of these species (Fig. 1).

Likewise, spatial distribution range changes were observed between the current scenarios and pessimistic scenarios (RCP 8.5; 2060 and 2080). The forecast models presented a reduction in adequacy both for the bee species and the passion fruit crop in several parts of the Neotropical region, particularly in Amazonian Forest. However, the high potential occurrence suitability for *X. frontalis, X. grisescens* and *P. edulis* seems continuous in the South America East coast covering large areas of NE and SE Brazil (Fig. 2). We observed that areas into the Southern-Center of Andes, between Peru and Bolivia, will become adequate for potential occurrence of *X. frontalis*. In turn, potential occurrence areas for *X. grisescens* will continue restricted to Brazil. In addition, other areas in the Neotropics will become suitable to potential occurrence of these bees, despite the absence of records for such species in these areas at present days (Figs. 1 and 2).

As for the passion fruit crop, the majority of the spatial distribution range will remain concentrated in Brazil despite reduction in suitable conditions for cropping. Present suitable areas to passion fruit crop in Amazonia will tend to reduce their potential adequacy in the moderate and pessimistic future scenarios. However, there may be an increase of new areas with suitable conditions for cropping passion fruits in specific locations in the Neotropic (Fig. 1 and 2).

The forecast models suggest that the species may shift their present occurrence areas toward new suitable areas in the Neotropics. The overlapping maps for the future scenarios show that *X. frontalis* gains new potential suitable areas and presents a potential shift of areas in forecast models RCP 4.5 (2060; 2080). These models predict potential area losses in relation to present days of 27.3 and 15.4%, but an overall potential increase in areas suitable to *X. frontalis* up to 35.6 and 75.1% (Table 1). However, the models RCP 8.5, for years 2060 and 2080, predict a reduction of 57.7% and 47.9% in the *X. frontalis* occurrence areas (Table 1).

Xylocopa grisescens may have a potential shift toward new areas in the moderate (RCP 4.5, 2060) up to 130.4%. However, the models show a reduction of suitable areas up to 35.3% in the pessimistic scenario in 2080 and in the other scenarios the reduction will be 15.4, 27.8 and 23.5% in the moderate (RCP 4.5; 2060 and 2080) and pessimistic (RCP 8.5; 2060) scenarios, respectively.

Passion fruit will be the species most affected by climate change in all future scenarios. According to model predictions, there will be a critical reduction of adequate potential areas for cropping passion fruit (RCP 4.5–44. 9 to −51.3%; RCP 8.5 = −42.9 for 2060 and 2080, respectively) up to 64.8% in the pessimistic scenario (RCP 8.5) in 2080, when comparing to the present days. This situation may cause reduction in productive areas and adequacy for passion fruit crop (Table 1).

When we compared the overlapping maps of the spatial range of bees and crops (Fig. 3), we observed a spatial mismatch between passion fruit and the bee species up to 42.8% in RCP 8.5 (2060) model, and observed a potential reduction in the potential suitable areas for coexistence of all species by 34.1 to 38.2% in the moderate scenarios (RCP 4.5; 2060, 2080, respectively) and 31.9 to 54.9% in the pessimistic scenarios (RCP 8.5; 2060 and 2080) (Table 2).

4. Discussion

We have shown that climate change may lead to changes in the natural range of *Xylocopa* bees, as well as suitable areas for cropping passion fruit, and a potential reduction in the overlapping areas between those suitable for bee species requirements and those adequate for passion fruit crops. Our results showed changes in the spatial distribution of *Xylocopa* bees and a reduction in the current areas of potential occurrence, representing loss of adequacy of these areas until the end of century 21th. An increase of non-adequate areas may lead to a decline in the abundance of these bee species in the affected regions, potentially fragmenting the population in these areas. Changes in the suitable areas and fragmentation of bee populations caused by climate change had also been forecasted by Giannini et al. (2013) in a study restricted to the Brazilian cerrado (Brazilian tropical savanna) considering the proportion of area loss by *Xylocopa* bees and wild plants used by them, in a moderate scenario for 2050. Our study expands these findings to the whole Neotropics, modeling also the crop and using the new IPCC recommendation for climatic scenario models (IPCC-AR5, 2013) including also the pessimistic scenario. We also estimated the actual size of area loss for bees and the crop which is very significant from the agricultural point of view.

In addition, we also observed that the regions with high abundance of *X. frontalis* and *X. grisescens* and current high occurrence potential tend to reduce in area and increase the species occurrence potential in future scenarios. Likewise, the bee species might shift toward presently unsuitable areas (e.g. Southern-Center of Andes) and this is one the reasons to the increase in the spatial distribution range area in some of our models. Nevertheless, it is important to note that suitable areas in the future will be potential refuges for species capable of reaching such

Table 1
Overlapping species range of potential occurrence areas in the current and future scenarios (RCP 4.5, 2060; 2080 and RCP 8.5, 2060; 2080) to species *Xylocopa frontalis* and *Xylocopa grisescens* and *Passiflora edulis* crop in the Neotropic.

Species	Scenarios	Current area	Potential lost area		Unchanged area	Potential gained area		Future area range	Area Change
		Km^2	Km^2	(%)	Km^2	Km^2	(%)	Km^2	%
Xylocopa frontalis	Current × RCP 4.5 (2060)	761,755.5	208,305.0	(27.34)	553,450.5	291,582.0	(35.68)	825,264.0	8.34
	Current × RCP 4.5 (2080)	761,755.5	117,904.5	(15.48)	643,851.0	438,547.5	(75.18)	1,216,566.0	59.70
	Current × RCP 8.5 (2060)	761,755.5	439,663.5	(57.71)	322,092.0	351,576.0	(9.77)	396,499.5	−47.95
	Current × RCP 8.5 (2080)	761,755.5	358,479.0	(47.06)	403,276.5	211,396.5	(18.03)	540,616.5	−29.03
Xylocopa grisescens	Current × RCP 4.5 (2060)	410,148.0	63,229.5	(15.41)	346,918.5	27,666.0	(130.43)	881,883.0	115.02
	Current × RCP 4.5 (2080)	410,148.0	114,066.0	(27.81)	296,082.0	127,485.0	(69.37)	580,590.0	41.56
	Current × RCP 8.5 (2060)	410,148.0	96,475.5	(23.52)	313,672.5	103,455.0	(69.11)	597,145.5	45.59
	Current × RCP 8.5 (2080)	410,148.0	144,859.5	(35.32)	265,288.5	373,099.5	(55.65)	493,533.0	20.33
Passiflora edulis	Current × RCP 4.5 (2060)	1,469,151.0	659,808.0	(44.91)	809,343.0	344,542.5	(5.882)	895,765.5	−39.03
	Current × RCP 4.5 (2080)	1,469,151.0	754,276.5	(51.34)	714,874.5	638,239.5	(3.436)	765,355.5	−47.90
	Current × RCP 8.5 (2060)	1,469,151.0	630,288.0	(42.90)	838,863.0	213,462.0	(6.343)	932,044.5	−36.56
	Current × RCP 8.5 (2080)	1,469,151.0	952,965.0	(64.86)	516,186.0	455,674.5	(1.192)	533,700.0	−63.67

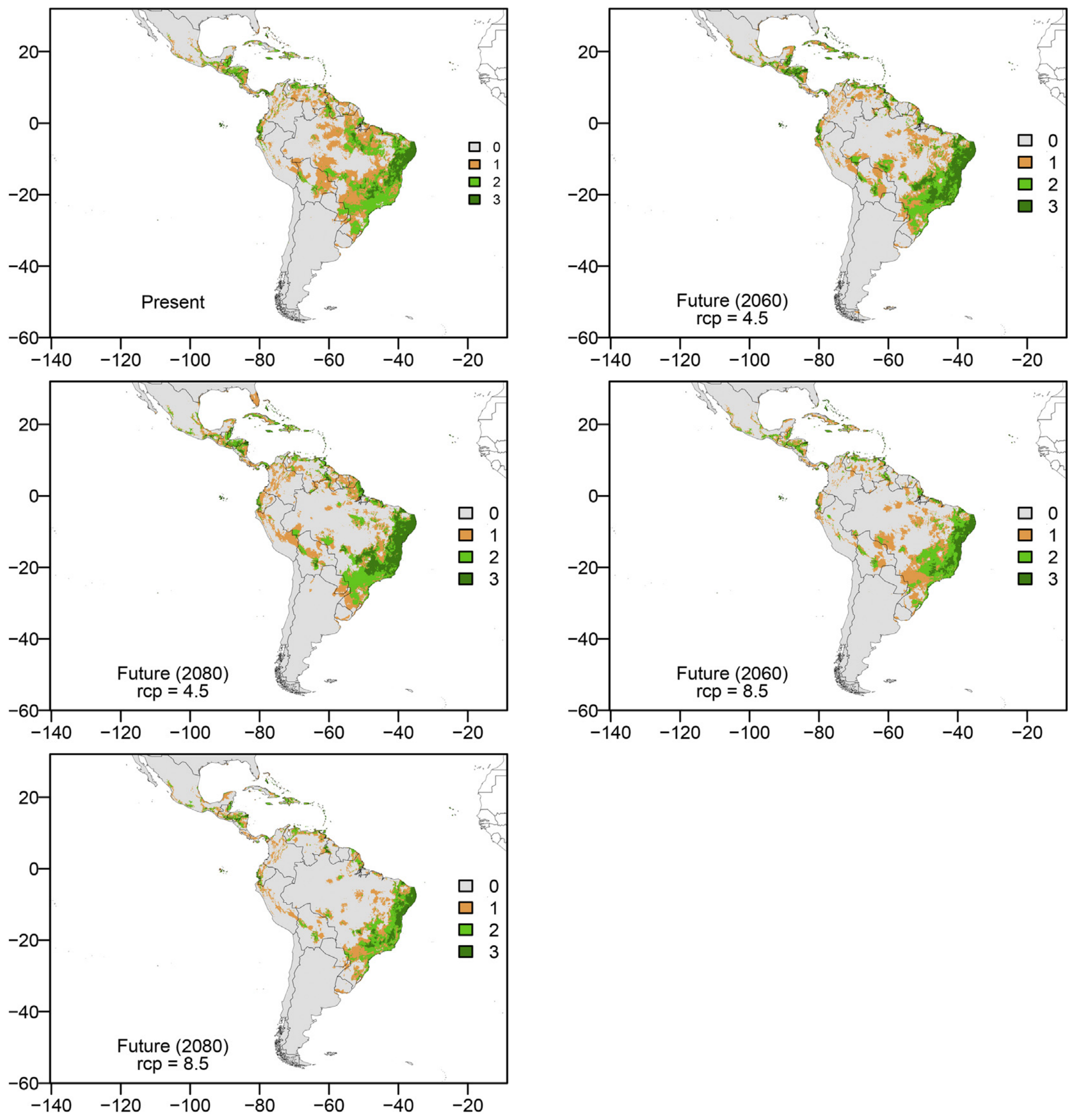

Fig. 3. Overlapping maps of *Xylocopa frontalis*, *Xylocopa grisescens* and passion fruit crop in the current scenario, moderate scenario (RCP 4.5) and pessimistic scenario (RCP 8.5) in years 2060 and 2080. Legend: 0 - indicates no species occurrence area; number 1 – one species occurrence area; number 2 – two species occurrence area; number 3 – three species occurrence area, in the Neotropical region.

areas (Schweiger et al., 2008; Foriester et al., 2010; Burkle et al., 2013). These species will have to overcome the matrix of barriers existing between the current areas of occurrence and new favorable areas in the future. But, we believe that many areas would not be reached naturally by these bees. Another way of these species reaching these areas would be by deliberate introduction.

Nevertheless, recent studies showed that climate changes are already altering the phenology of species, abundance and spatial distribution of some pollinators in the past decades (Hegland et al., 2009; Kerr et al., 2015; Oliver et al., 2015). In this sense, some pollinators are changing their spatial distribution range from previously suitable sites to new areas previously unable to support them, but that are now becoming adequate, while others seem to be less able to adjust to changes (Parmesan et al., 1999; Foriester et al., 2010; Burkle et al., 2013; Polce et al., 2014; Settele et al., 2016).

In the same sense, Giannini et al. (2017) points out that climate changes, in a pessimistic scenario, would harm the agricultural crop production in Brazil, including the passion fruit crop. In this scenario, a decrease on the occurrence of the pollinator species in several Brazilian counties would reduce the overlapping areas between agricultural crop and their pollinators. However, this study concentrated only on climate change effects on the pollinators assuming that cropping areas in the future would be the same as today. Here, we were able to estimate also the suitable areas to passion fruit in the future scenarios, and we observed reduction in the adequate areas for passion fruit orchards in all scenarios. Furthermore, in relation to the present situation, our estimates point out to a reduction in the overlapping of the areas suitable to the pollinator bees and the passion fruit crop in the future potentially increasing over 50% pollinator mismatch and suggesting that the effects on this crop may be greater than those projected by Giannini et al. (2017).

The reduction of areas adequate for cropping passion fruit may harm not only crop production, but also the region in which passion fruit orchards are economically important. This spatial distribution mismatch between species will cause the pollination services to become more vulnerable, which consequently may affect crop production (Settele et al., 2016). Spatial mismatch between agricultural crops and their pollinators had already been estimated for temperate agricultural crops such as apple (*Malus domestica*), pear (*Pyrus communis*) and plum (*Prunus domestica*), and model projections indicate that climate change will lead to losses of overlapping areas due to lack of adequate climatic conditions for the coexistence of crops and pollinators (Polce et al.,

Table 2
The potential areas (Km^2) of overlapping between the *Passiflora edulis* crop and its bee pollinators, *Xylocopa frontalis* and *X. grisescens*, in the current and future scenario in the Neotropics.

Crop	Bees	Scenarios	Area					
			Only bees present		Bees and crop present		Only crop present	
			Km^2	(%)	Km^2	(%)	Km^2	(%)
Passiflora edulis	*Xylocopa frontalis*	Current	195,669.0	(100)	566,086.5	100	903,064.5	(100)
		RCP 4.5 (2060)	314,671.5	(60.82)	510,592.5	(−9.80)	385,173.0	(−57.35)
		RCP 4.5 (2080)	609,484.5	(211.49)	607,081.5	(7.24)	158,274.0	(−82.47)
		RCP 8.5 (2060)	114,574.5	(−41.44)	281,925.0	(−50.20)	650,119.5	(−28.01)
		RCP 8.5 (2080)	270,117.0	(38.05)	270,499.5	(−52.22)	263,200.5	(−70.85)
	Xylocopa grisescens	Current	56,380.5	(100)	353,767.5	(100)	1,115,384	(100)
		RCP 4.5 (2060)	365,431.5	(548.15)	516,451.5	(45.99)	379,314.0	(−65.99)
		RCP 4.5 (2080)	222,403.5	(294.47)	358,186.5	(1.25)	407,169.0	(−63.50)
		RCP 8.5 (2060)	185,026.5	(228.17)	412,119.0	(16.49)	519,925.5	(−53.39)
		RCP 8.5 (2080)	251,176.5	(345.50)	242,356.5	(−31.49)	291,343.5	(−73.88)
	Carpenter bees(*X. frontalis* and *X. grisescens*)	Current	222,934.5	(100)	545,481.0	(100)	736,483.5	(100)
		RCP 4.5 (2060)	520,632.0	(133.54)	359,064.0	(−34.17)	202,711.5	(−72.48)
		RCP 4.5 (2080)	623,340.0	(179.61)	336,996.0	(−38.22)	114,223.5	(−84.49)
		RCP 8.5 (2060)	271,116.0	(21.61)	371,061.0	(−31.98)	399,492.0	(−45.76)
		RCP 8.5 (2080)	396,949.5	(78.06)	245,655.0	(−54.97)	154,444.5	(−79.03)

Passion fruit crop potential occurrence area. Current = 1,469,151.0 km^2; RCP 4.5 (2060) = 895,765.5 km^2; RCP 4.5 (2080) = 765,355.5 km^2; RCP 8.5 (2060) = 932,044.5 km^2; RCP 8.5 (2080) = 533,700.0 km^2; *X. frontalis* potential occurrence area. Current = 761,755.5 km^2; RCP 4.5 (2060) = 1,216,566.0 km^2, RCP 4.5 (2080) = 396,499.5 km^2; RCP 8.5 (2060) = 396,499.5 km^2; RCP 8.5 (2080) = 540,616.5 km^2; *X. grisescens* potential occurrence area. Current = 410,148.0 km^2; RCP 4.5 (2060) = 881,883.0 km^2; RCP 4.5 (2080) = 580,590.0 km^2; RCP 8.5 (2060) = 597,145.5 km^2; RCP 8.5 (2080) = 493,533.0 km^2.

2014).

Our work is the first conducted with a tropical crop and bees, which considers potential changes in adequate areas for both pollinators and the plant species. It reveals not only a reduction in suitable areas for passion fruit orchards, but also for the co-occurrence areas of the three species, which will accentuate the spatial mismatch between the crop and their main pollinators in the Neotropics.

In addition, indirect effects may further impact the scenarios for the species studied (Brown et al., 2016). For example, studies suggest that global warming can also lead to temporal mismatch leading to loss of spatial co-occurrence, which may directly affect the phenology of some plant species and the plant-pollinator interactions, which would become less robust in modified landscapes (Kjøhl, et al., 2011; Burkle et al., 2013; Vanbergen et al., 2013; Polce et al., 2014, Settele et al., 2016). Changes of climatic factors lead to phenological incompatibility that mainly affects specialized pollinators, but also reduces the variation of generalist bee diet (e.g. *Xylocopa* bees) consequentially decreasing the availability of resources to the species (Vanbergen et al., 2013). At the same time, alterations of climatic factors may also act directly on the agricultural crop, changing its phenology, flowers morphologies, sex ratios and the nectar chemistry, affecting the attractiveness to the bees (Hoover et al. 2012).

Climate change threatens the natural pollination of passion fruit crops and it is necessary to develop strategies to mitigate these effects. According to the IPCC (2013), in all RCPs scenarios, the global average temperature will increase 0.3 to 4.8 °C in the end of 21th. Although, the passion fruit is a species that naturally lives in a heterogeneous phytogeographic environment due to its physiological threshold, there is no certainty that plant breeders could select and develop varieties capable of survival and productivity under the new environmental scenarios to prevent great area losses. In this case, the lack of pollinators in passion fruit orchards can be compensated by hand pollination, although this labor results in increase of production costs (Junqueira et al. 2013) and currently there is shortage of workers in the field to carry out this work. The use of pollinator-friendly practices in areas where there is loss of bee population density, for example, the conservation of forests and border fragments near orchard areas, may also result in the conservation of *Xylocopa* populations close to the crop, especially because these bee species use dead wood as nesting substrate and could use floral resources from these areas (Kremen et al., 2002; Giannini et al., 2013). Finally, *Xylocopa* can be reared and managed to mitigate pollination deficits in orchard of passion fruit lacking their wild pollinators (Freitas and Oliveira-Filho, 2003; Oliveira-Filho and Freitas, 2003).

Based on the models forecasting climate change, in the future scenarios moderate and pessimistic, we conclude that the suitable areas to co-occurrence of passion fruit crop and its effective pollinators will be largely affected in the Neotropics. Although the *Xylocopa* bee species studied in the present study may occupy new areas, as well as remain in sites they are currently present, there will be a significant reduction in suitable areas for the overlapping of the passion fruit crop and its pollinator bees, in part because many areas will become unsuitable to passion fruit orchards. Likewise, new suitable areas for the crop will be unsuitable for one or both pollinator bee species. Steps to mitigate the effects of the climate changes should be taken to ensure viable populations of pollinators in the areas suited to passion crop both through management of the agricultural areas and surrounding landscapes. Breeding and management of *Xylocopa* bees should also be implemented.

Acknowledgement

Breno M. Freitas thanks CNPq – National Council for Scientific and Technological Development, Brasília – Brazil for the Productivity in Research sponsorship (#308948/2016-5). This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001. Guy Smagghe also thanks the Special Research Fund of the Ghent University and the Research Foundation - Flanders (FWO-Vlaanderen) in supporting his research with pollinators. The authors thank all researchers that provided the data and databases, especially *SpeciesLink* and GBIF – Global Biodiversity Information Facility.

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